

Studying Structure Formation with the Sloan Digital Sky Survey

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Abstract. I review some of the recent results from the SDSS related to galaxies and large scale structure, including: (1) discovery of coherent, unbound structures in the stellar halo of the Milky Way, (2) demonstration that the Pal 5 globular cluster has tidal tails and that the Draco dwarf spheroidal does not, (3) precise measurement of the galaxy luminosity function and its variation with galaxy surface brightness, color, and morphology, (4) detailed examination of the Fundamental Plane from a sample of 9000 early type galaxies, (5) measurement, via galaxy-galaxy lensing, of the extended dark matter distributions around galaxies and their variation with galaxy luminosity, morphology, and environment, (6) measurements of the galaxy angular power spectrum and of the spatial correlation function and pairwise velocity dispersion as a function of galaxy luminosity and color. I then turn to a more abstract discussion of what we can hope to learn, in the long run, from galaxy clustering in the SDSS and the 2dFGRS. The clustering of a galaxy sample depends on the mass function and clustering of the dark halo population, and on the Halo Occupation Distribution (HOD), which specifies the way that galaxies populate the halos. Hydrodynamic simulations and semi-analytic models of galaxy formation make similar predictions for the probability $P(N|M)$ that a halo of virial mass M contains N galaxies of a specified type: a non-linear form of the mean occupation $N_{\text{avg}}(M)$, sub-Poisson fluctuations about the mean in low mass halos, and a strong dependence of $N_{\text{avg}}(M)$ on the age of a galaxy's stellar population. Different galaxy clustering statistics respond to different features of the HOD, making it possible to determine the HOD empirically given an assumed cosmological model. Furthermore, changes to Ω_m and/or the linear power spectrum produce changes in the halo population that would be difficult to mask by changing the HOD. Ultimately, we can hope to have our cake and eat it too, obtaining strong guidance to the physics of galaxy formation by deriving the HOD of different classes of galaxies, while simultaneously carrying out precision tests of cosmological models.

1. The SDSS: Goals and Status

The observational goals of the SDSS have remained stable since its early days: (1) u,g,r,i,z CCD imaging of 10^4 deg^2 in the North Galactic Cap, to a depth

~ 23 mag in the most sensitive bands, (2) a spectroscopic survey in this area of 10^6 galaxies, 10^5 quasars, and an assortment of stars and other targets, and (3) imaging of three $2.5^\circ \times 90^\circ$ stripes in the South Galactic Cap, with the equatorial stripe scanned repeatedly to allow variability studies and co-added imaging that goes ~ 2 mag deeper than a single scan. The normal spectroscopic program is carried out on all three stripes in the south, and additional spectroscopy in the equatorial stripe will provide deeper samples of quasars and galaxies and more comprehensive coverage of stellar targets. The survey is carried out using a dedicated 2.5-m telescope on Apache Point, New Mexico, equipped with a mosaic CCD camera (Gunn et al. 1998) and two fiber-fed double spectrographs that can obtain 640 spectra simultaneously (Uomoto et al., in preparation). A technical overview of the survey appears in York et al. (2000), and an updated but more focused technical summary appears in the paper by Stoughton et al. (2002) that describes the Early Data Release. The quasar survey is reviewed by Schneider et al. (these proceedings), and the quasar target selection is described by Richards et al. (2002). There are two samples in the galaxy redshift survey, a magnitude limited sample to $r = 17.77$ comprising 90% of the galaxy targets (Strauss et al. 2002), and a sparser, deeper sample of luminous red galaxies (Eisenstein et al. 2001).

After a decade of preparatory work, the SDSS formally began operations on the auspicious date of April 1, 2000. It is planned to run until summer, 2005. The total area covered will depend on the weather between now and then, especially the amount of weather that satisfies the seeing and photometric requirements of the imaging survey. A reasonable guess is that the northern survey will cover $\sim 70\%$ of the original 10^4 deg² goal by summer, 2005. As of January, 2002, the SDSS had obtained ~ 3200 square degrees of imaging and $\sim 230,000$ spectra (of which about 80% are galaxies), including both northern and southern observations. The quality of the spectra, which cover the wavelength range 3800Å to 9200Å at resolution $R \sim 1800$, is spectacular. Redshift completeness for spectroscopically observed galaxies is over 99%, and for most galaxies the spectra yield stellar velocity dispersions and valuable diagnostics of the stellar populations. The scientific analyses to date are only scratching the surface of what the spectroscopic data allow.

In June, 2001, the SDSS released 462 deg² of imaging data (~ 14 million detected objects) and 54,000 follow-up spectra obtained during commissioning observations and the first phases of the survey proper, as documented by Stoughton et al. (2002). In addition to providing data for the larger community, the Early Data Release is a training exercise for the SDSS collaboration. One lesson is that releasing data as complex as that in the SDSS (e.g., radial profiles plus over 80 measured parameters for each photometric object, some of which are deblended, some imaged on more than one scan, some observed spectroscopically) in a useful way is very challenging, even within the collaboration itself. The First Data Release will take place in January, 2003, and subsequent releases will take place on a roughly annual basis (see <http://www.sdss.org/science/index.html>).

This paper is based on two talks that I gave at the *New Era in Cosmology* conference. Section 2 reviews some of the recent SDSS results on galaxies and large scale structure; the topics mentioned are some of the ones that I have found interesting myself, and they by no means constitute a comprehensive list. All of

these results are published or available on **astro-ph**, so my summaries are brief and do not include figures. In Section 3, I discuss what we can hope to learn from studying galaxy clustering in the SDSS and the 2dFGRS, with focus on the Halo Occupation Distribution as a way of thinking about the relation between galaxies and dark matter. This discussion is based on collaborative work with Andreas Berlind, Zheng Zheng, Jeremy Tinker, and others.

2. A Review of Recent Results

2.1. Substructure in the Milky Way

The first science results from the SDSS that really surprised me were the discoveries, made independently by Yanny et al. (2000) using A-colored stars and by Ivezić et al. (2000) using RR Lyrae candidates, of coherent, unbound structures in the Milky Way's stellar halo, stretching across tens of degrees. The idea that the stellar halo might be built by mergers of dwarf galaxies is an old one (Searle & Zinn 1978), and much of the recent theoretical modeling has focused on detecting fossil substructure through phase space studies of the local stellar distribution (e.g., Johnston et al. 1995; Helmi & White 1999; Helmi & de Zeeuw 2000). Even in the absence of kinematic data, the SDSS is a powerful tool for detecting substructure in the outer halo because multi-color imaging allows the definition of samples of stars that are approximately standard candles. The two structures found by Yanny et al. (2000), in an area $\sim 1\%$ of the sky, may both be associated with the tidal stream of the Sagittarius dwarf galaxy (Ibata et al. 2001). However, a recent study using F-stars (Newberg et al. 2001) appears to show several more substructures, and no clear indication that there is a smooth underlying halo at all. Extending a model originally developed to investigate the dwarf satellite problem, Bullock, Kravtsov, & Weinberg (2001) showed that the population of disrupted dwarfs expected in the CDM cosmological scenario could naturally account for the entire stellar halo. If this model is right, then the SDSS should reveal ubiquitous substructure in the outer halo, where orbital times are long and the number of discrete streams is relatively small. In any event, the SDSS imaging survey will answer fundamental questions about the origin of the Milky Way's stellar halo, and perhaps about the amount of power on sub-galactic scales in the primordial fluctuation spectrum.

2.2. Milky Way Satellites

With multi-color data, one can define optimal filters to maximize the contrast between an object in the Milky Way or Local Group and the foreground and background stellar distributions. Odenkirchen et al. (2001ab) have developed this technique and applied it to great effect in studies of the globular cluster Pal 5 and the dwarf spheroidal Draco. Pal 5 shows two well defined tidal tails that contain $\sim 1/3$ of the cluster's stars, demonstrating that the cluster is subject to heavy mass loss. The orientation of the tails reveals the projected direction of the cluster's orbit, and peaks within the tails may be a signature of disk shocking events. Draco, on the other hand, shows no sign of tidal extensions even at surface densities $\sim 10^{-3}$ of the central value, demonstrating that it is a bound, equilibrium system, and justifying standard kinematic estimates that yield a

high mass-to-light ratio, $M/L_i \sim 100 - 150$. As the SDSS covers more sky, we will get a more complete census of which objects are being tidally destroyed and which are still holding themselves together. Tidal tails and tidal streams may also provide valuable constraints on the radial profile, shape, and clumpiness of the Milky Way's dark halo potential (see, e.g., Johnston et al. 1999).

2.3. The Galaxy Luminosity Function

Blanton et al. (2001) measured the galaxy luminosity function in u , g , r , i , and z using a sample of 11,275 galaxies observed during SDSS commissioning observations. The large sample size, accurate photometry, and use of the Petrosian (1976) system for defining galaxy magnitudes yield small statistical errors and excellent control of systematic effects. This analysis confirms and quantifies previous indications that the galaxy luminosity function varies systematically with surface brightness, color, and morphology; the first correlation implies that low surface brightness galaxies make only a small contribution to the mean luminosity density of the universe. The measured luminosity density exceeds the R -band estimate from the Las Campanas Redshift Survey (Lin et al. 1996) by a factor of two, and Blanton et al. show that this difference arises from the isophotal magnitude definition adopted by the LCRS, which misses light in the outer parts of galaxies that have intrinsically low or cosmologically dimmed surface brightness.

Norberg et al. (2001b) demonstrate convincingly that the high-precision measurement of the b_J -band luminosity function from the 2dFGRS is in good agreement with the luminosity function measured by the SDSS. Two main factors caused Blanton et al. (2001) to reach a contrary conclusion: they used an inaccurate conversion from SDSS bands to b_J , and their maximum likelihood method effectively estimates the luminosity function at a redshift $z \approx 0.1 - 0.15$, while the method used by Norberg et al. (2001b) implicitly corrects for evolution to derive the $z = 0$ luminosity function. Using the SDSS early release data, Norberg et al. (2001b) demonstrate excellent agreement in the mean between SDSS and 2dFGRS galaxy magnitudes and redshifts, and they confirm earlier estimates of the completeness and stellar contamination of the 2dFGRS input catalog. While the optical luminosity function estimates are now in good agreement, there remains a puzzling discrepancy pointed out by Wright (2001) between the luminosity density found in the optical bands by the SDSS and the estimates of the K_s -band luminosity density from the 2dFGRS and 2MASS data (Cole et al. 2001; see also Kochanek et al. 2001). Norberg et al. (2001b) argue that the discrepancy is probably dominated by large scale structure fluctuations in the area used to normalize the K_s -band luminosity function.

2.4. Properties of Early Type Galaxies

The SDSS data are ideal for studying the correlations of galaxy properties, since the photometric and spectroscopic reduction pipelines measure many quantities automatically and one can create large samples with well understood selection effects. The main effort to date in this area is the comprehensive study of a sample of 9000 early type galaxies by Bernardi et al. (2001). They determine the fundamental plane in the g , r , i , and z bands, and they measure bivariate correlations among luminosity, size, velocity dispersion, color, mass-to-light ratios,

and spectral indices. The large sample size and high precision allow examination of relatively subtle effects, such as a slight difference in the fundamental plane of “field” and “cluster” galaxies. The evolution of the fundamental plane over the redshift range of the sample (which extends to $z \approx 0.2$) is consistent with passive evolution of old stellar populations.

2.5. Galaxy-Galaxy Lensing

One of the most dramatic breakthroughs from the SDSS has been the measurement of galaxy mass profiles and the galaxy-mass correlation function via galaxy-galaxy weak lensing. Systematic effects are much easier to control for galaxy-galaxy lensing than for cosmic shear measurements because image distortion is measured perpendicular to the radial separation vector, which has a different orientation for each foreground-background pair. The large area gives the SDSS great statistical power despite its rather shallow imaging (by weak lensing standards).

Fischer et al.’s (2000) analysis of two nights of SDSS imaging data (225 deg²) was at the time the clearest detection of a galaxy-galaxy lensing signal, with extended shear profiles (to $r \gtrsim 250h^{-1}$ kpc) offering direct evidence for the extended dark matter halos expected in standard models of galaxy formation. McKay et al. (2001) have since analyzed a sample of $\sim 3,600,000$ source galaxies around $\sim 35,000$ foreground galaxies in the spectroscopic sample, measuring the galaxy-mass correlation function and its dependence on galaxy luminosity, morphology, and environment. They find that the mass within an aperture of $260h^{-1}$ kpc scales linearly with galaxy luminosity, that the excess mass density around galaxies in high density regions remains positive to $r \sim 1h^{-1}$ Mpc while that around isolated galaxies is undetectable beyond $\sim 300h^{-1}$ kpc, and that early type galaxies have a higher amplitude galaxy-mass correlation function, in part because of their preferential location in group environments. Guzik & Seljak (2002) have modeled the McKay et al. results to infer that L_* galaxies have virial masses $M \sim (5 - 10) \times 10^{11}h^{-1}M_\odot$, implying that a large fraction of the baryons within the virial radius of an L_* galaxy halo end up as stars in the central galaxy. By comparing to the Tully-Fisher relation, Seljak (2002) concludes that circular velocities at the halo virial radius are typically a factor $\sim 1.7 - 1.8$ below the values measured at the galaxy optical radius, and in reasonably good agreement with predictions based on CDM halo profiles.

2.6. Angular Galaxy Clustering

Early efforts to study galaxy clustering with the SDSS have focused on the analysis of a $2.5^\circ \times 90^\circ$ stripe of imaging data that has been closely examined and reduced multiple times. Scranton et al. (2001) carried out an exhaustive analysis of possible systematic effects associated with seeing variations, stellar density, Galactic reddening, galaxy deblending, variations across the imaging camera, and so forth, showing that they have no significant impact on measurements of the angular correlation function at the obtainable level of statistical precision. These experiments demonstrate that star-galaxy separation in the SDSS imaging works extremely well to $r \approx 22$. Dodelson et al. (2001) modeled the measurements of the angular correlation function (Connolly et al. 2001) and the angular power spectrum (Tegmark et al. 2001), to infer the 3-dimensional clus-

tering of galaxies. Their results, $\sigma_8 \approx 0.8 - 0.9$, $\Gamma \approx 0.15$, are consistent with those obtained by Szalay et al. (2001) applying a different method, Karhunen-Loeve parameter estimation, to the same galaxy catalog. The statistical error bars from these analyses are not yet competitive with the highest precision analyses of the galaxy power spectrum (e.g., Percival et al. 2001), but they provide reassuring evidence that any systematic biases in the SDSS imaging data, and thus in the input to the redshift survey, are well controlled. Recently Szapudi et al. (2001) have analyzed the higher order angular moments of this data set, finding agreement with the hierarchical scalings and values of skewness and kurtosis parameters predicted by Λ CDM models that incorporate mild suppression of galaxies in high mass halos. With the analysis tools now developed and tested and the systematic issues apparently well understood, the analyses of larger sky areas should soon yield precise measurements of angular clustering over a wide dynamic range.

2.7. Clustering in the Redshift Survey

Zehavi et al. (2001) carried out the first analysis of clustering in the SDSS redshift survey, focusing on the real space correlation function $\xi(r)$ and the pairwise velocity dispersion $\sigma_{12}(r)$ for different classes of galaxies, with a sample similar in size and geometry to the LCRS. Galaxies in absolute magnitude bins centered on $M_* - 1.5$, M_* , and $M_* + 1.5$ have parallel power-law correlation functions with slopes $\gamma \approx -1.8$, but their amplitudes are significantly different, with $r_0 \approx 4.7$, 6.3, and $7.4h^{-1}$ Mpc, respectively. The correlation function of red galaxies is both steeper and higher amplitude than that of blue galaxies. The pairwise dispersion for the full sample is $\sigma_{12} \approx 600 \text{ km s}^{-1}$ at $r \sim 1h^{-1}$ Mpc, but red galaxies have $\sigma_{12} \sim 700 \text{ km s}^{-1}$ and blue galaxies only $\sigma_{12} \sim 400 \text{ km s}^{-1}$. The dependence of $\xi(r)$ on galaxy properties resembles that found by Norberg et al. (2001ac) in the 2dFGRS (and in earlier studies such as Guzzo et al. 1997), but there are significant differences of detail. The SDSS data show a steady trend of correlation strength with luminosity, while Norberg et al. (2001a) find a transition from weak dependence below L_* to strong dependence above L_* . Norberg et al. (2001c) find similar $\xi(r)$ slopes for galaxies of different spectral types, while the correlation function of blue galaxies in the SDSS is clearly shallower than that of red galaxies. Analysis of larger SDSS samples should clarify the significance of these differences; the first could reflect the difference between r -band and b_J -band selection, and the second could represent a difference between color and spectral type as a basis for galaxy classification. A consequence of the SDSS observing strategy (dictated largely by the instruments themselves) is that the early redshift data had a 2-dimensional slice geometry, making it difficult to study the large scale power spectrum and statistics that require contiguous 3-d volumes, like void probabilities and topology. That situation is changing as the survey progresses, and first results on these topics should emerge over the next several months.

2.8. Random Optimistic Remarks

The SDSS collaboration involves hundreds of scientists, with eleven participating institutions on three continents. With such a large and far-flung collaboration, we spend a lot of energy just keeping ourselves organized. I have just finished

my term as the SDSS Scientific Publications Coordinator, a position with one chief benefit: I was forced to pay attention as the scientific output of the SDSS grew from a trickle to a flood, spreading rivulets into many different areas of astronomy. This development has been exciting to watch, and I have learned a lot of astronomy just by following it. While there are certainly challenges of communication in a collaboration this large, the process of going from data to science has worked, in my opinion, remarkably well. The ideal scenario is that each scientific analysis draws on the collective expertise of a very broad spectrum of astronomers; I have been delighted to see how often we approach this ideal in practice. The richness of the SDSS data is more than enough to keep us busy. Indeed, while I am sure that we look enormous from the outside, it is constantly evident from the inside that we don't have enough people to do all the science we would like to be doing. That, of course, is one of many good reasons for publishing the data.

Before completely shifting gears, let me pause to congratulate the members of the 2dF galaxy and quasar redshift surveys for (a) obtaining more than 200,000 spectra, (b) publishing more than 100,000 spectra, and (c) writing a number of beautiful papers analyzing the results and implications. All three of these are great achievements. While the SDSS and 2dF teams cannot help but see themselves in competition every now and then, the benefits to astronomy of having these independent data sets and independent analyses are already very clear.

3. What Can We Learn From Galaxy Clustering?

The above question is one that has been pondered by many people over several decades. Two developments that color recent considerations of this subject are the extraordinary improvements in the quantity and quality of the redshift survey data and the convergence of the cosmological community on a “standard” model, Λ CDM, that is supported by an impressive base of observational evidence. A third development that has deeply affected my own thinking is the emergence of a new way of describing galaxy bias, the Halo Occupation Distribution (HOD). The HOD characterizes the statistical relation between galaxies and mass in terms of the probability distribution $P(N|M)$ that a halo of virial mass M contains N galaxies, together with prescriptions that specify the relative spatial and velocity distributions of galaxies and dark matter within these halos. Note that “halo” here refers to a structure of typical overdensity $\rho/\bar{\rho} \sim 200$, in approximate dynamical equilibrium; higher density cores within a group or cluster are, in this description, treated as substructure, and characterized only in a statistical sense. Since different types of galaxies have different space densities and different clustering properties, a given HOD applies to a specific class of galaxies, e.g., red galaxies brighter than L_* , or late-type spirals with r magnitudes -17 to -19 . The HOD framework has roots in early analytic models that described galaxy clustering as a superposition of randomly distributed clusters with specified profiles and a range of masses (Neyman & Scott 1952; Peebles 1974; McClelland & Silk 1977). A bevy of recent papers have shown that, when combined with numerical or analytic models of the clustering of the halos themselves, the HOD is a powerful tool for analytic and numerical calculations of

clustering statistics, for modeling observed clustering, and for characterizing the results of semi-analytic or numerical studies of galaxy formation (e.g., Jing, Mo, & Börner 1998; Benson et al. 2000; Ma & Fry 2000; Peacock & Smith 2000; Seljak 2000; Berlind & Weinberg 2001; Marinoni & Hudson 2001; Scoccimarro et al. 2001; Yoshikawa et al. 2001; White, Hernquist, & Springel 2001; Bullock, Wechsler, & Somerville 2002).

My own interest in this approach was spurred largely by the paper of Benson et al. (2000), who discussed the clustering predictions of their semi-analytic model of galaxy formation in these terms. A forthcoming paper by Berlind et al. (in preparation; see also Berlind 2001) compares the predictions of the Benson et al. semi-analytic formalism to those of a large, smoothed particle hydrodynamics (SPH) simulation (Murali et al. 2001; Davé et al., in preparation), for the same cosmological model. The agreement between the two approaches is remarkably good. If we select galaxies above a specified baryon mass threshold, chosen separately in the two calculations so that the space densities of the populations are equal, then the mean occupation $N_{\text{avg}}(M)$ is a non-linear function of mass with three basic features: a cutoff mass below which halos are not massive enough to host a galaxy above the threshold, a low occupancy regime ($N_{\text{avg}} \lesssim 2$) in which the mean occupation grows slowly with increasing halo mass but the average galaxy mass itself increases, and a high occupancy regime in which $N_{\text{avg}}(M)$ grows more steeply with mass, though the growth is still sub-linear because larger, hotter halos convert a smaller fraction of their baryons into galaxies. In the low occupancy regime, the fluctuations about the mean are well below those of a Poisson distribution — a halo that is supposed to host one galaxy very rarely hosts two — and the sub-Poisson nature of these fluctuations has a crucial impact on some clustering statistics. The HOD is strongly dependent on the age of the galaxies’ stellar populations; old galaxies like to live together in massive, high occupancy halos, while young galaxies studiously avoid them. The SPH simulations further show that the oldest, most massive galaxy in a halo usually resides near the halo center and moves at close to the center-of-mass velocity, while the remaining galaxies approximately trace the spatial and velocity distribution of the halo’s dark matter. The agreement between the semi-analytic and SPH calculations, despite some clear differences in the way that they treat radiative cooling and feedback from star formation, suggests that the HOD emerges from fairly robust physics that both methods do right, given their common assumptions. Whether these assumptions hold in the real universe is, of course, one of the things we hope to learn.

Figure 1 sketches the interplay between the “Cosmological Model” and the “Galaxy Formation Theory” in determining galaxy clustering (which I take to include the galaxy-mass correlations measured by weak lensing). The HOD approach suggests a nice division of labor between these two theoretical inputs. The cosmological model, which specifies the initial conditions (e.g., scale-invariant fluctuations from inflation) and the matter and energy contents (e.g., Ω_m , Ω_b , Ω_ν , Ω_γ , Ω_Λ), determines the mass function, spatial correlations, and velocity correlations of the dark halo population. At our adopted overdensity threshold $\rho/\bar{\rho} \sim 200$, these properties of the halo population are determined almost entirely by gravity, with no influence of complex gas physics. I have inserted a box in the path between cosmological model and dark halo population to indicate that the only features of the cosmological model that really matter in this con-

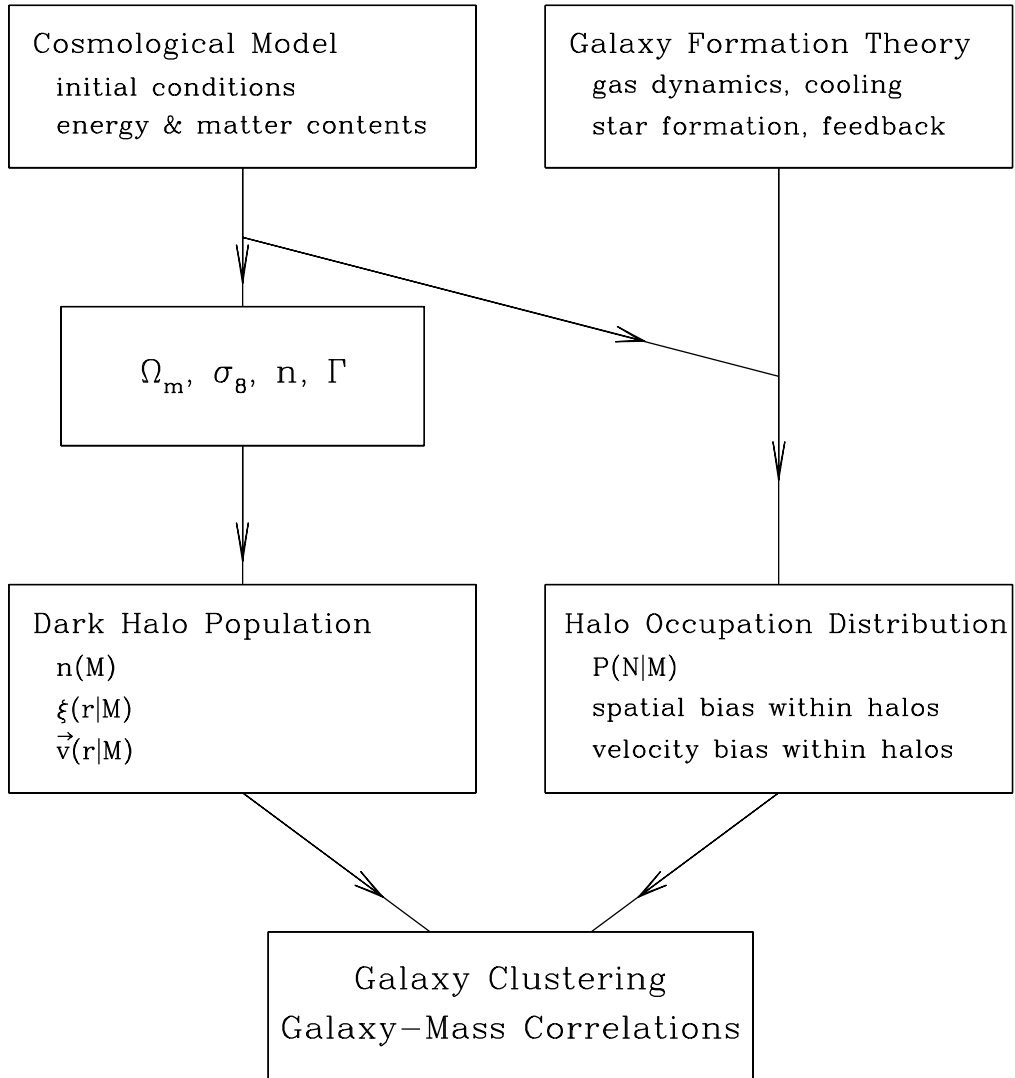


Figure 1. The interplay between the cosmological model and the galaxy formation theory in determining galaxy clustering and galaxy-mass correlations.

text are Ω_m , the fluctuation amplitude (represented here by σ_8), and the power spectrum shape (represented here by n and Γ , though it could, of course, be more interesting). Other features of the cosmological model, such as the energy density and equation of state of the vacuum component, may have an important impact on other observables or on the *history* of matter clustering, but they have virtually no effect on the halo population at $z = 0$, if the shape of $P(k)$ and the present day value of σ_8 are held fixed. The galaxy formation theory incorporates the additional physical processes — such as shock heating, radiative cooling, conversion of cold gas into stars, and feedback of star formation on the surrounding gas — that are essential to producing distinct, dense, bound clumps of stars and cold gas. It further specifies what aspects of a galaxy’s formation history determine its final mass, luminosity, diameter, color, morphology, and so forth. These physical processes operate in the background provided by the evolving halo population, so the predicted HOD depends on both the theory of galaxy formation and the assumed cosmological model.

As a description of bias, the crowning virtue of the HOD is its completeness: given a dark halo population and a fully specified HOD, one can predict the value of any galaxy clustering statistic, on any scale, using analytic approximations and/or numerical simulations.¹ Berlind & Weinberg (2001) examined the influence of the HOD on galaxy clustering and galaxy-mass correlations, for the halo population of a Λ CDM N-body simulation. We found that different clustering statistics, or even the same statistic at different scales, are sensitive to different aspects of the HOD. For example, at large scales $\xi_{gg}(r)$ is proportional to the mass correlation function $\xi_{mm}(r)$, with a bias factor equal to the average of the halo bias factor $b_h(M)$ weighted by the halo number density and the mean occupation $N_{\text{avg}}(M)$. On small scales, however, the explicit dependence on $\xi_{mm}(r)$ disappears, and $\xi_{gg}(r)$ depends on the halo mass function, on the mean number of pairs $\langle N(N-1) \rangle$ as a function of halo mass and virial radius, and (to a lesser extent) on the internal bias between galaxy profiles and mass profiles. Connecting these pieces into a power-law galaxy correlation function is a rather delicate balancing act, and the success of SPH simulations and semi-analytic models in reproducing the observed form of $\xi_{gg}(r)$ given a Λ CDM cosmology is entirely non-trivial; the reduced efficiency of galaxy formation in high mass halos and the sub-Poisson fluctuations in low mass halos are both crucial to this success. Higher order correlation functions place greater weight on the high mass end of the halo population and on higher moments of $P(N|M)$. The void probability function, on the other hand, depends mainly on the low mass cutoff of the HOD, which determines the probability of finding galaxies in the low mass halos that populate large scale underdensities. The pairwise velocity dispersion has distinct regimes much like $\xi_{gg}(r)$, but it depends little on the low mass cutoff and strongly on the relative occupation of high and low mass halos, and the sub-Poisson fluctuations that depress $\xi_{gg}(r)$ at small scales *boost* the pairwise dispersion by forcing those pairs that do exist at these separations

¹There is one caveat here, namely the implicit assumption that a halo’s galaxy content depends, on average, only on its mass, and has no statistical correlation with the halo’s large scale environment. This assumption is adopted in “merger tree” formulations of the semi-analytic method, and it is supported by the N-body experiments of Kauffmann & Lemson (1999) and by the results of the SPH simulation mentioned above, but it is not logically incontrovertible.

to come from higher mass halos. The pairwise dispersion can also be influenced by velocity bias of galaxies within halos. The group multiplicity function bears a quite direct relation to the HOD, to such an extent that one can “read off” $N_{\text{avg}}(M)$ if $P(N|M)$ is reasonably narrow and one assumes an underlying halo mass function $n(M)$. Peacock & Smith (2000) and Marinoni & Hudson (2001) have applied variants of this approach to observational data and obtained results that agree rather well with the SPH and semi-analytic predictions, assuming a Λ CDM halo mass function.

Berlind and I concluded that an empirical determination of the HOD should be possible given high precision clustering measurements and the halo population of an assumed cosmological model. This, at a minimum, is what we can expect to learn from galaxy clustering: the halo occupation distributions of many different classes of galaxies, given a cosmological model motivated by independent observations. Because the HOD description of bias is complete, these HODs encode everything that galaxy clustering has to teach us about galaxy formation. They encode it, moreover, in a physically informative way, allowing detailed tests of theoretical predictions and providing rather specific guidance when these predictions fail. If your theory of galaxy formation does almost everything right but puts too many blue-ish S0 galaxies in $10^{13} - 10^{14} M_{\odot}$ halos, then you might have some ideas on how to fix it.

Can we have our cake and eat it too? In more precise words, if we find a combination of cosmological model and HOD that matches all the galaxy clustering data, can we conclude that both are correct, or might there be other combinations that are equally successful?

To decide whether cosmology and bias are degenerate with respect to galaxy clustering, we must first know how changing the cosmology alters the halo population. This issue is the subject of a forthcoming paper by Zheng et al., where we investigate the effect of changing Ω_m on its own, of changing Ω_m and σ_8 simultaneously while maintaining “cluster normalization” ($\sigma_8 \Omega_m^{0.5} = \text{constant}$), and of changing Ω_m and σ_8 in concert with n or Γ . The impact of a pure Ω_m change is simple: the halo mass scale M_* shifts in proportion to Ω_m , pairwise velocities (at fixed M/M_*) are proportional to $\Omega_m^{0.6}$, and halo clustering at fixed M/M_* is unchanged. Cluster normalized changes to Ω_m and σ_8 keep the space density of halos approximately constant near $M \sim 5 \times 10^{14} h^{-1} M_{\odot}$, and halo clustering and pairwise velocities remain similar at fixed M . However, the shape of the halo mass function changes, with a decrease of Ω_m from 0.3 to 0.2 producing a $\sim 30\%$ drop in the number of low mass halos. One can preserve the shape of the mass function over a large dynamic range by changing n or Γ , but the required changes are substantial — e.g., masking a decrease of Ω_m from 0.3 to 0.2 requires $\Delta n \approx 0.3$ or $\Delta \Gamma \approx 0.15$. These changes to the power spectrum significantly alter the halo clustering and halo velocities.

The sensitivity of the halo population to the cosmological model parameters is encouraging, because these changes cannot easily be masked by changing the HOD. For a pure Ω_m shift, one could keep the spatial clustering of galaxies the same by using the same HOD as a function of M/M_* , but the change would be detected by any dynamically sensitive clustering statistic, like large scale redshift-space distortions, the pairwise velocity dispersion, the galaxy-mass correlation function, or direct measurements of group and cluster masses. Even ve-

locity bias within halos could not hide all of these changes. A cluster-normalized change to σ_8 and Ω_m would require a change in galaxy occupation as a function of M/M_* in order to maintain the galaxy space density and group multiplicity function, and this change would affect other measures of galaxy clustering. A simultaneous change to the power spectrum shape that preserved the halo mass function would change galaxy clustering by changing the clustering of the halos themselves.

It remains to be seen just how well one can do quantitatively from realistic observations. The proof, ultimately, must await the pudding, but Zheng has begun to investigate the question in a somewhat idealized context. As a starting point, he takes clustering measures predicted by a Λ CDM cosmology with the HOD derived from the SPH simulations, calculated by a variety of analytic approximations. He then changes the assumed cosmology, thus changing the halo mass function and halo clustering, and he allows the HOD to change as well, using a parametrized form that gives flexibility in all of the essential features. He finds the HOD that gives minimum χ^2 for the original clustering “measurements,” which are assumed to have 10% fractional uncertainties, and the value of $\Delta\chi^2$ for the best-fit HOD indicates the acceptability of the cosmological model. The preliminary results from this exercise are encouraging. For example, in the case of pure Ω_m changes, the galaxy correlation function and group multiplicity function constrain the HOD tightly enough that measurements of $\beta = \Omega_m^{0.6}/b$ or the pairwise velocity dispersion impose useful constraints on Ω_m . As the SDSS and 2dFGRS measurements take shape, we can imagine taking a similar approach to the real data, albeit with careful attention to the accuracy of the clustering approximations. In terms of Figure 1, the surveys provide us with the entries in the lowest box, and using them, we search for maximum likelihood solutions for the parameters in the second boxes on the left and right hand sides. Despite what might at first appear to be a lot of freedom, the degeneracies appear to be limited, and we can hope to do rather well.

Here, then, is my conjectural answer to the question posed in the section title: we can learn the HOD of different classes of galaxies, gaining physical insight into their origin, and we can separately determine Ω_m and the amplitude and shape of the linear theory power spectrum, from the largest scales probed by the surveys (where perturbation theory describes the dark matter and the HOD fixes the “bias factors” needed to connect galaxies to mass) down to moderately non-linear scales (below which information about the linear power spectrum may be effectively erased, at least as far as the halo mass function and halo clustering are concerned). We can also test for any departures from Gaussian primordial fluctuations. We get these cosmological constraints *without* relying on a detailed theory of galaxy formation, only on the basic tenet that the HOD formulation itself is valid. While we might be wary of relying on conclusions that involve complicated corrections for galaxy bias, the observed dependence of clustering on galaxy type allows powerful cross-checks. When we analyze different classes of galaxies, we should derive different HODs, but we should always reach the same conclusions about the underlying cosmological model. If we do, then we have good reason to think that we are doing things right.

Given all the other methods that can constrain cosmology with tracers that are less physically complicated, one might wonder what galaxy clustering and

galaxy-mass correlations have to contribute to cosmological tests, beyond a reassuring consistency check. After all, how important is the second decimal place on Ω_m ? While I hear variants of this question often, I think it is a red herring, and that we should be relentless in our efforts to squeeze as much cosmological information as possible out of galaxy redshift surveys. Even if we assume that there will be no major conceptual adjustments to the current leading model, there are at least two fundamental issues on which precision measurements from galaxy clustering can play a critical role: the contribution (if any) of gravity waves to CMB anisotropy, and the equation of state of dark energy. The first can be addressed by a precise comparison between the CMB fluctuation amplitude and the present day amplitude of matter fluctuations. Evidence for or against gravity waves would take us much further in understanding the origin of density fluctuations, and perhaps even to understanding the mechanism (inflation, colliding branes, ...) that accounts for the size and homogeneity of the universe. Galaxy clustering has no sensitivity to the equation of state on its own, but the sensitivity of other tests depends crucially on precise knowledge of Ω_m , where the combination of galaxy clustering and galaxy-galaxy lensing may ultimately provide the best constraints. Precise knowledge of today's fluctuation amplitude is also essential to some tests for the equation of state and its time dependence (see, e.g., the discussion of Kujat et al. 2001).

Constraining gravity waves, the dark energy equation of state, and neutrino masses are concrete goals that we can set for cosmological applications of galaxy clustering. But we should not assume that the simplest model consistent with the current data (which already contains at least one very surprising element) will remain consistent with improving observations. A break in the inflationary fluctuation spectrum, a relativistic background inconsistent with standard neutrino physics, a baryon density inconsistent with big bang nucleosynthesis, a small admixture of non-Gaussian or isocurvature fluctuations — all of these are departures from the standard model whose quantitative impact would be subtle but whose physical implications would be profound. What we will learn from the 2dF and SDSS galaxy surveys depends in large part on what the universe has to teach us, and that is something we cannot yet know. Finding out is an exciting task for the New Era in Cosmology.

I am grateful to my numerous colleagues in the SDSS for producing the exciting results that I have recapitulated in §2, and for their efforts and progress in producing a data set that warrants the theoretical musings in §3. I thank my collaborators on the work discussed in §3, especially Andreas Berlind, Zheng Zheng, and Jeremy Tinker, whose contributions to the ideas and to the results have been central. I thank the NSF for its support of this research program and the Institute for Advanced Study and the Ambrose Monell Foundation for hospitality and support during the recent phases of this work. More details about the SDSS, including links to the Early Data Release, an ever-growing list of scientific publications based on the SDSS data, and a list of the many participating institutions and funding agencies that have made the survey possible, can be found at the official SDSS web site, <http://www.sdss.org>.

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